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(54) **LIGHT ABSORPTION AND SCATTERING DEVICES IN A PHOTONIC INTEGRATED CIRCUIT THAT MINIMIZE OPTICAL FEEDBACK AND NOISE**

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G02B 6/26 (2006.01)
G02B 6/28 (2006.01)

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CPC **G02B 6/12004** (2013.01); **G02B 6/12014** (2013.01); **G02B 6/2813** (2013.01)

(58) **Field of Classification Search**
CPC G02B 6/12004; G02B 6/2813; G02B 6/12014; G02B 6/12; G02B 6/26
USPC 385/12, 14–16, 24
See application file for complete search history.

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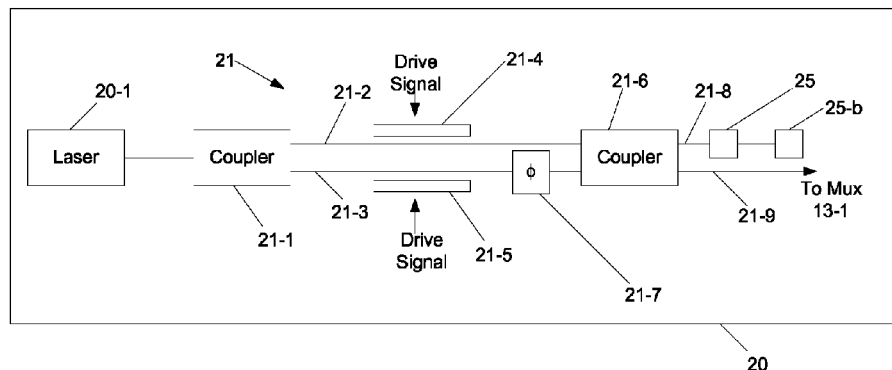
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(57) **ABSTRACT**

A photonic integrated circuit is provided that may include a substrate; one or more optical sources, on the substrate, to output light associated with a corresponding one or more optical signals; one or more waveguides connected to the one or more optical sources; a multiplexer connected to the one or more waveguides; and one or more light absorptive structures, located on the substrate adjacent to one of the one or more optical sources, one of the one or more waveguides, and/or the multiplexer, to absorb a portion of the light associated with at least one of the corresponding one or more optical signals.

12 Claims, 20 Drawing Sheets



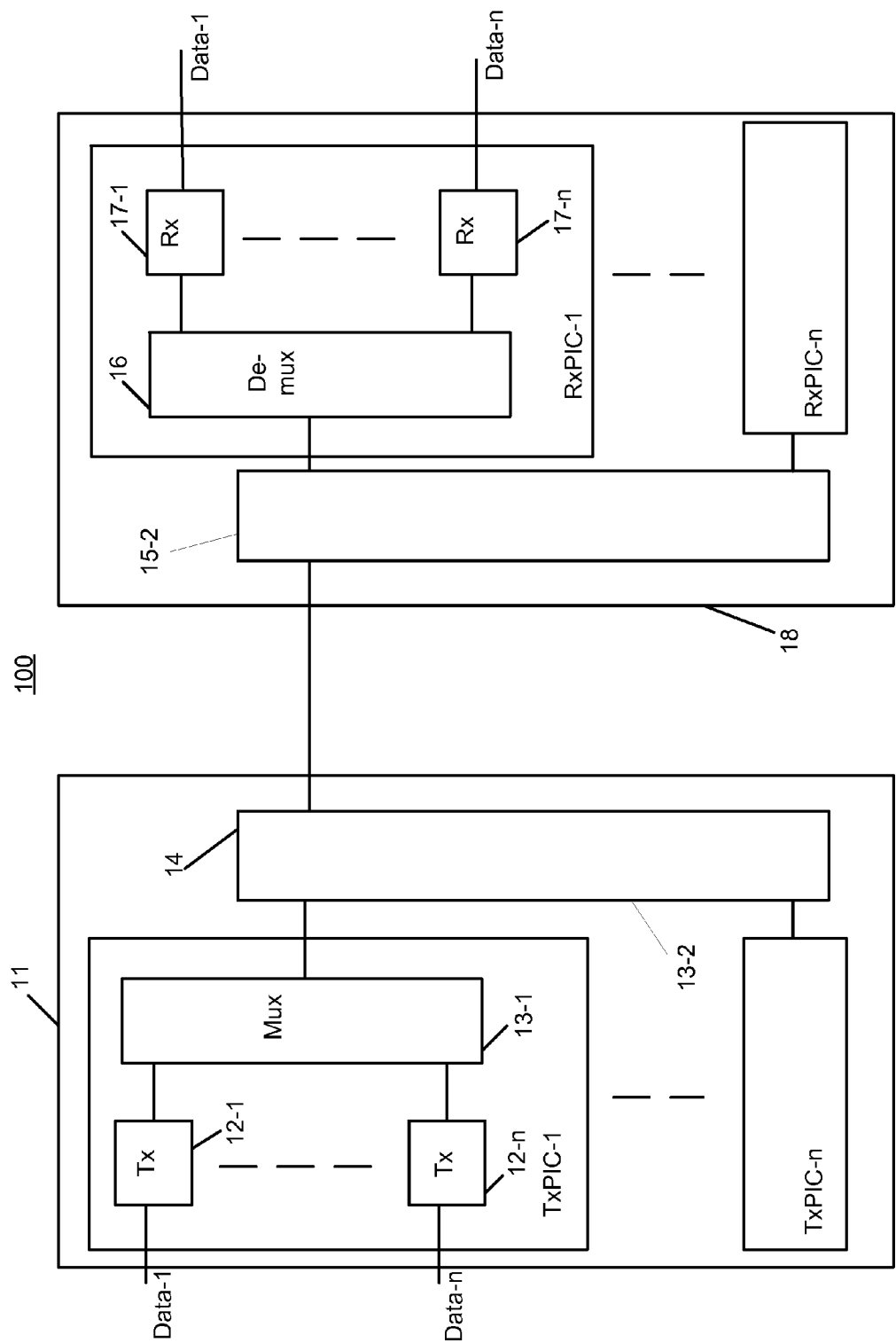
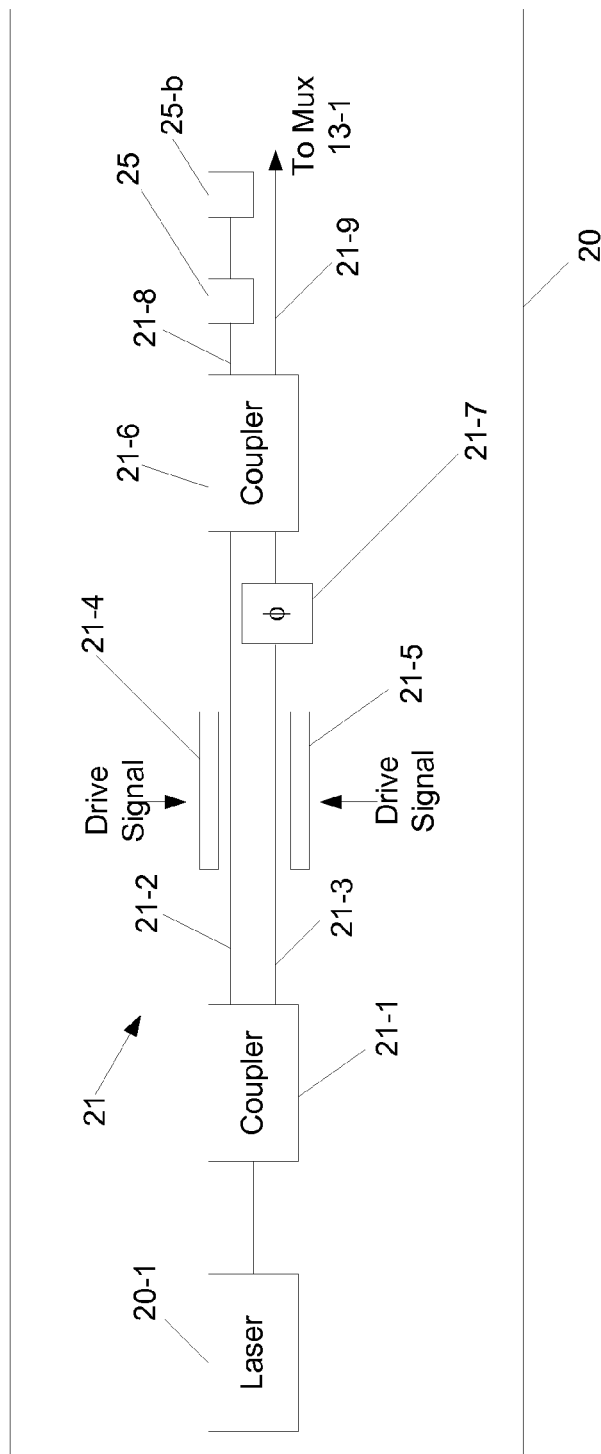


Fig. 1



IX 12-1

Fig. 2a

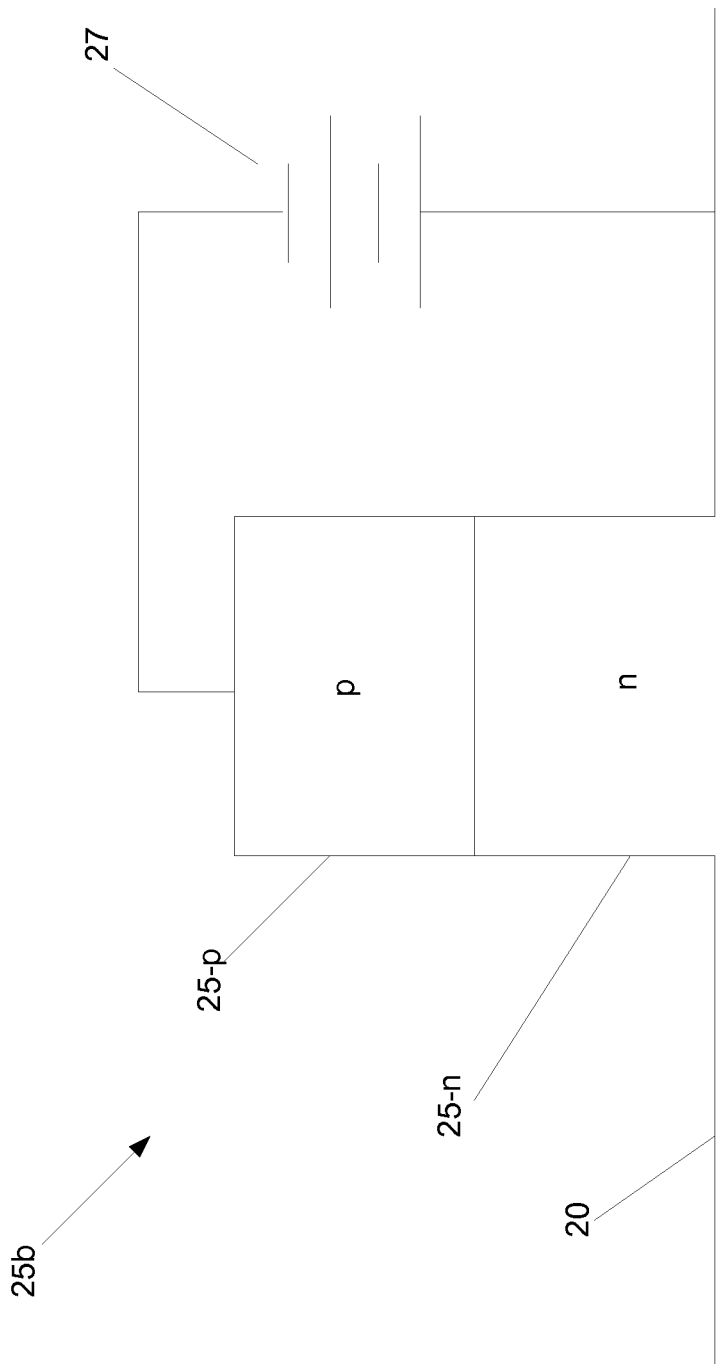


Fig. 2b

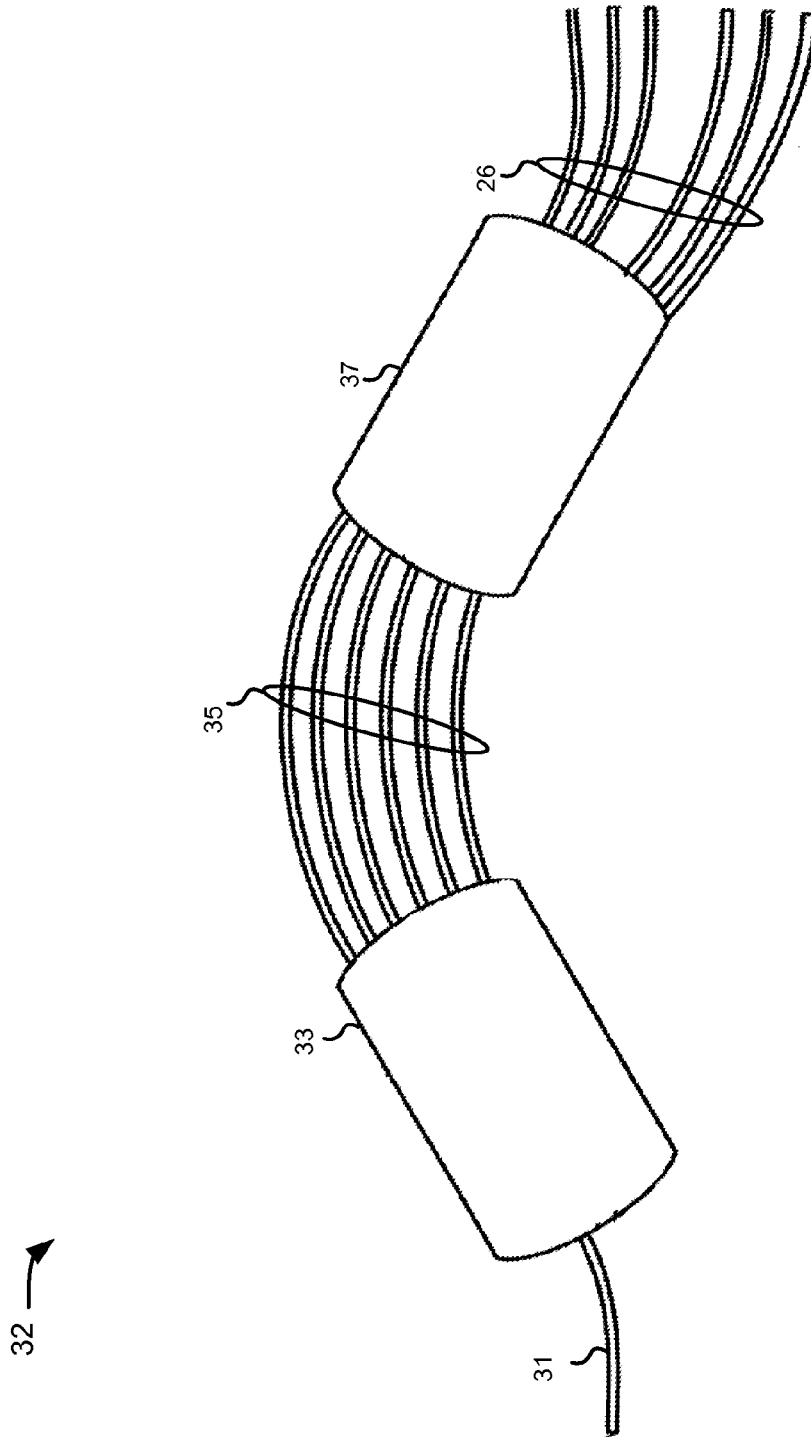
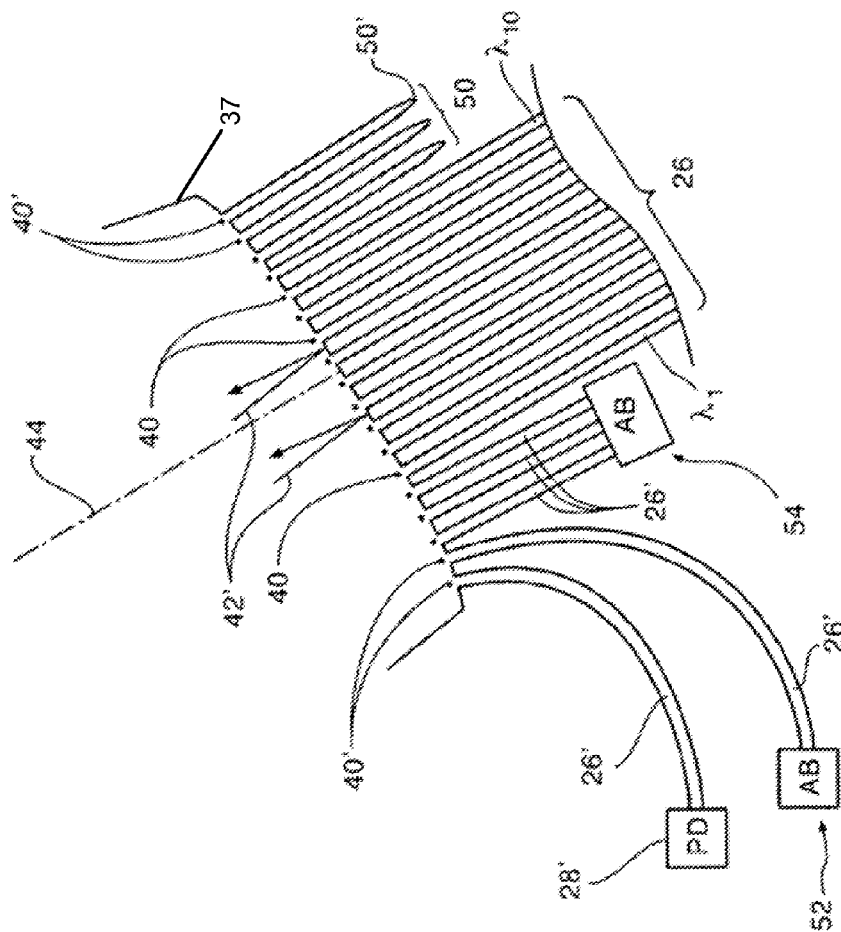


Fig. 3

Fig. 4



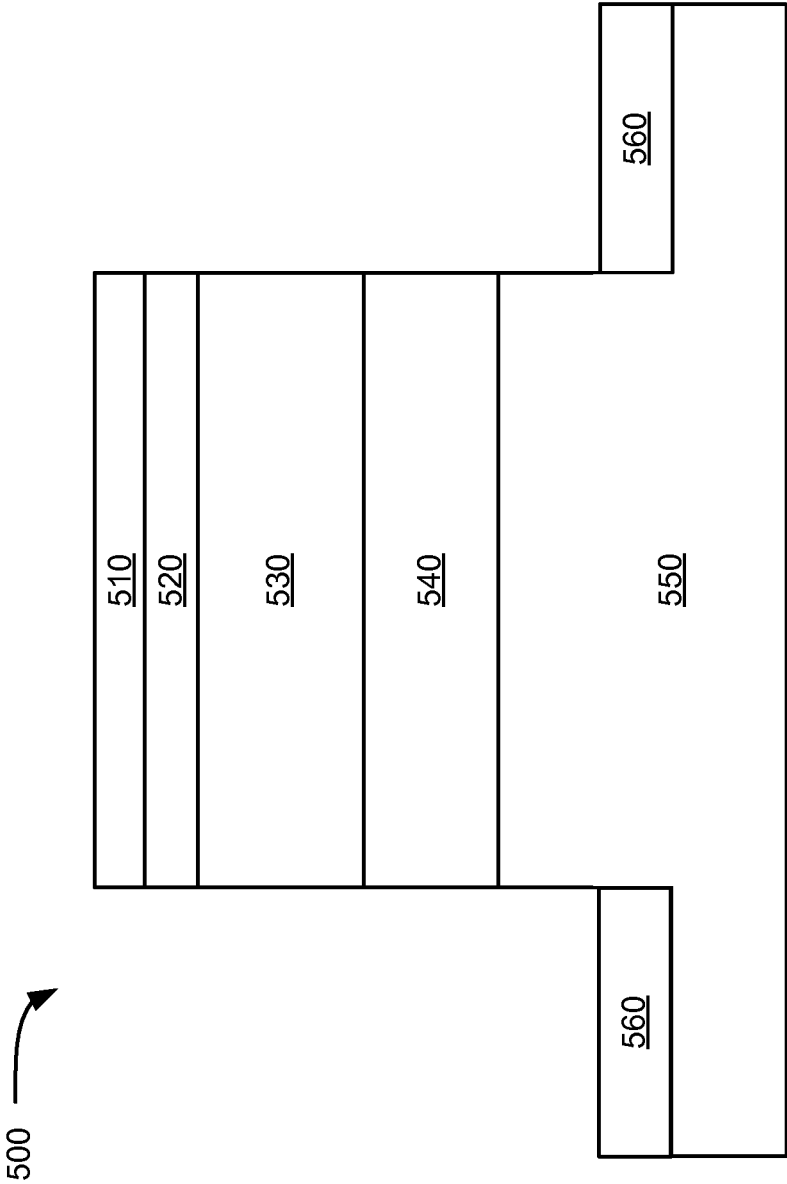


Fig. 5

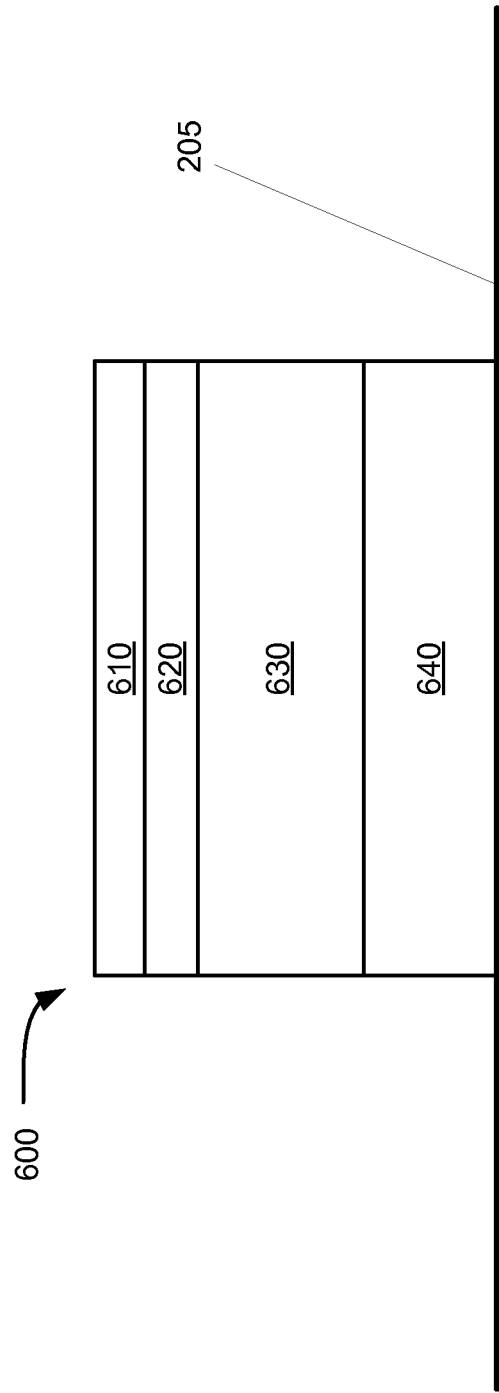


Fig. 6

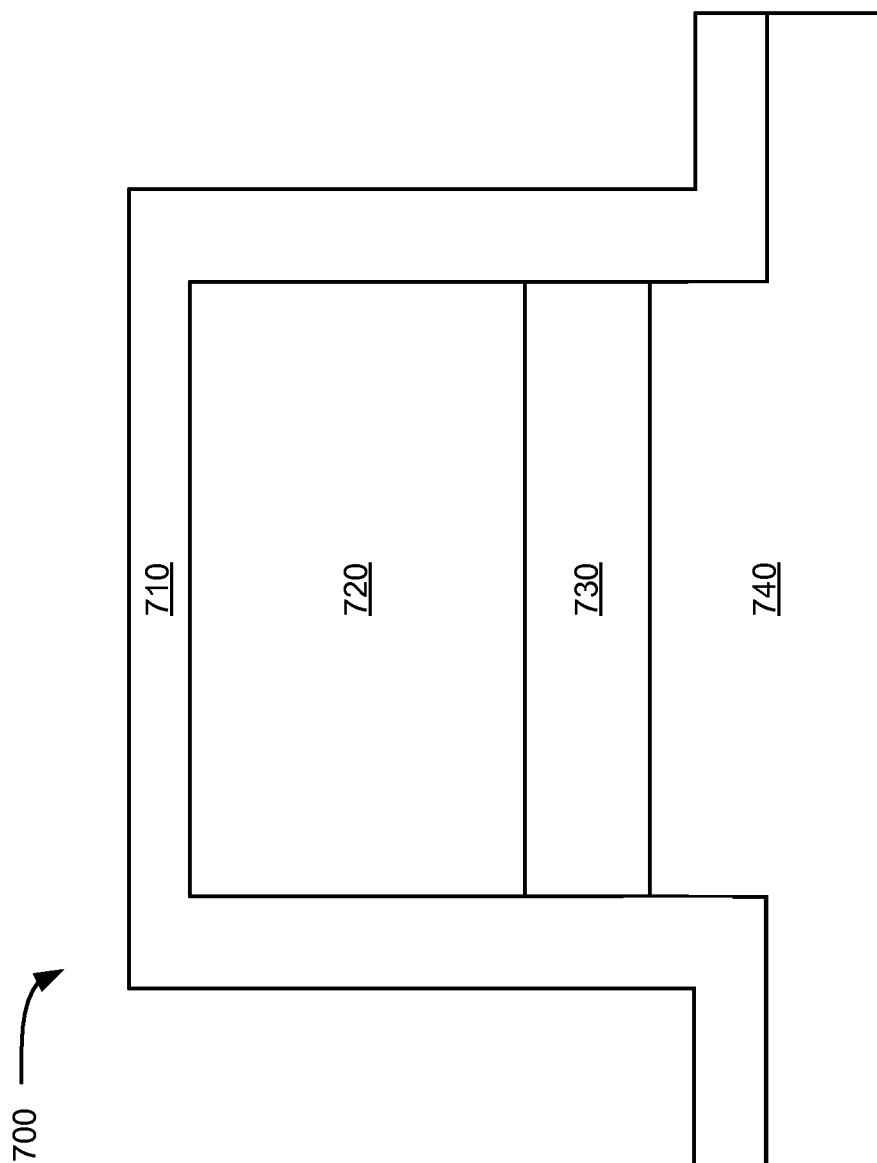


Fig. 7a

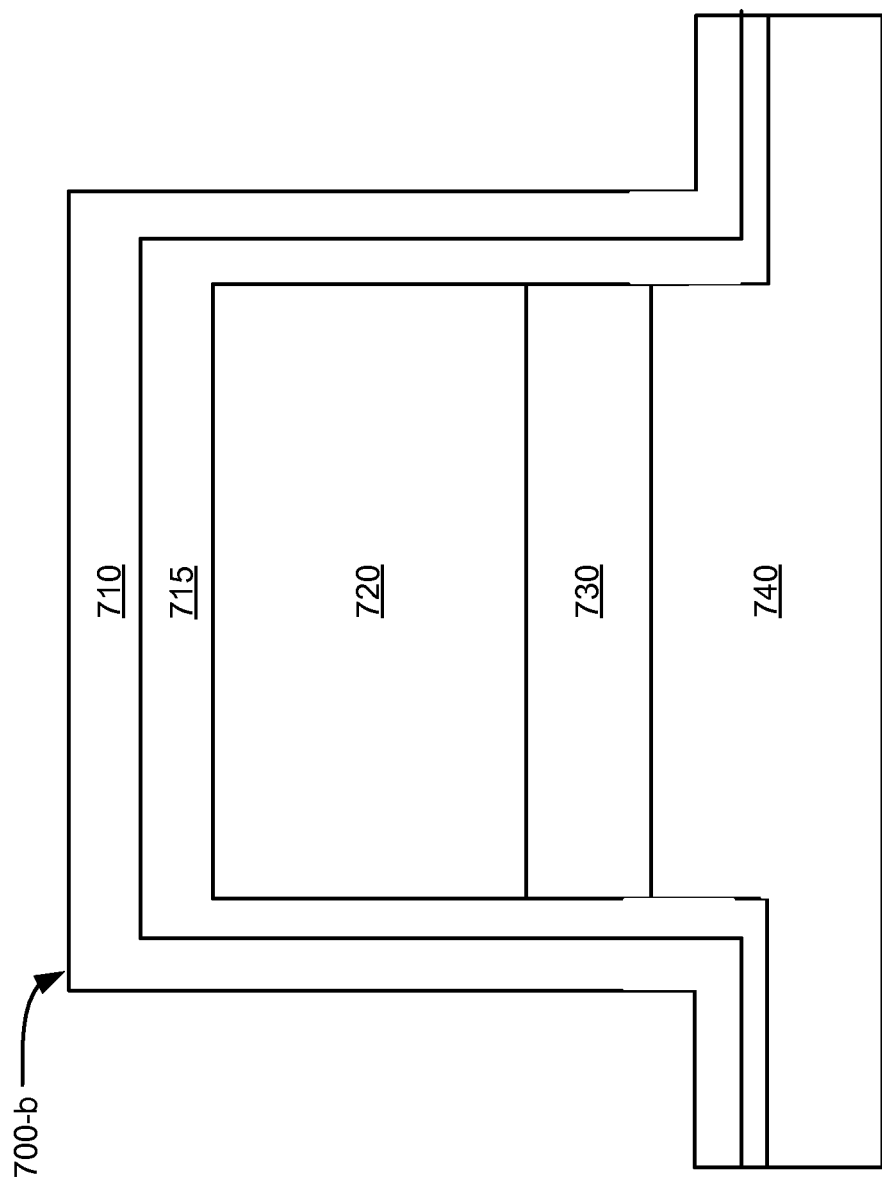


Fig. 7b

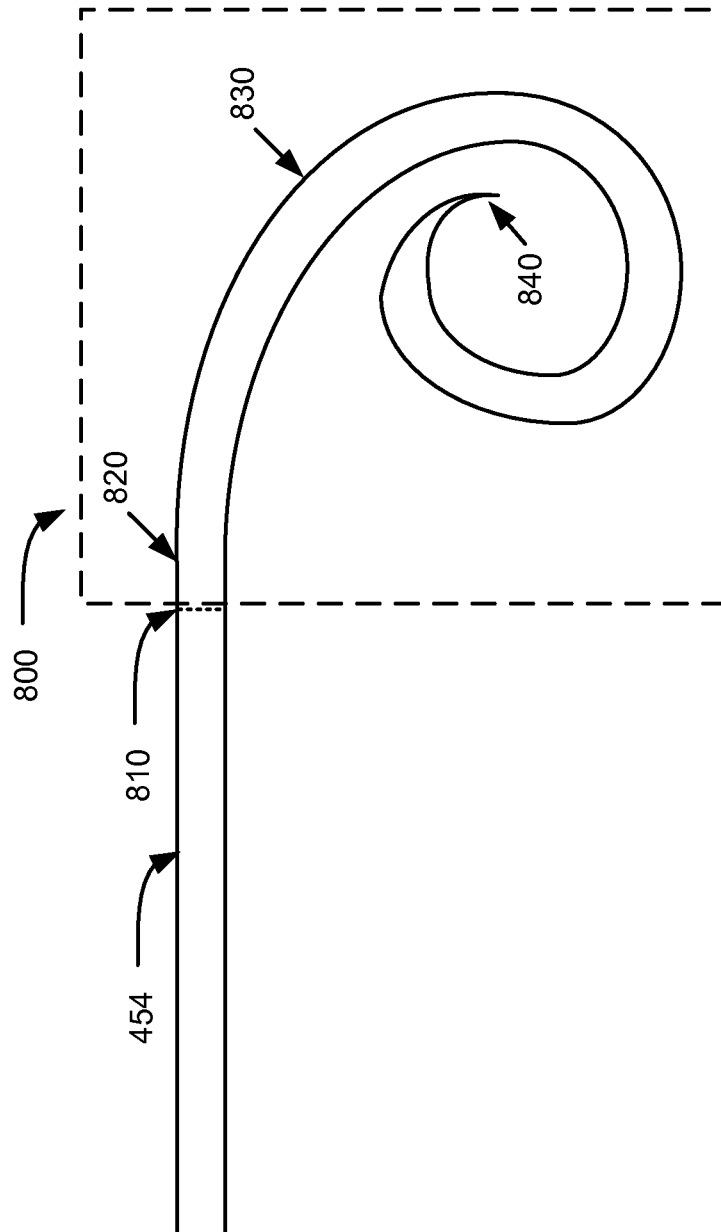


Fig. 8

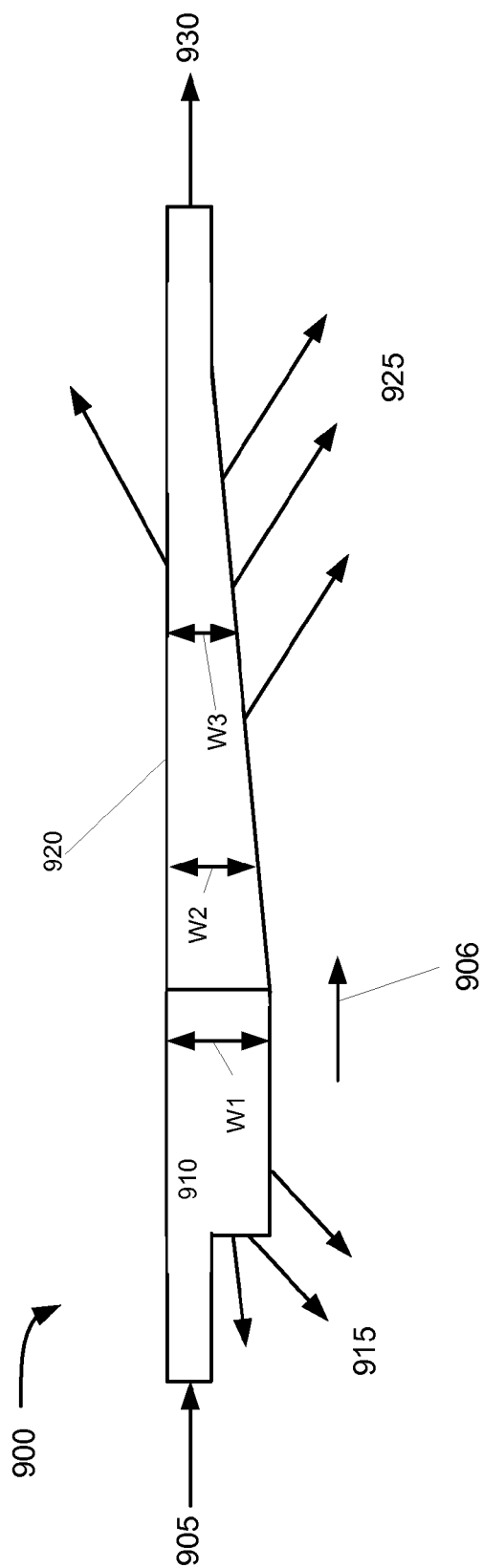


Fig. 9

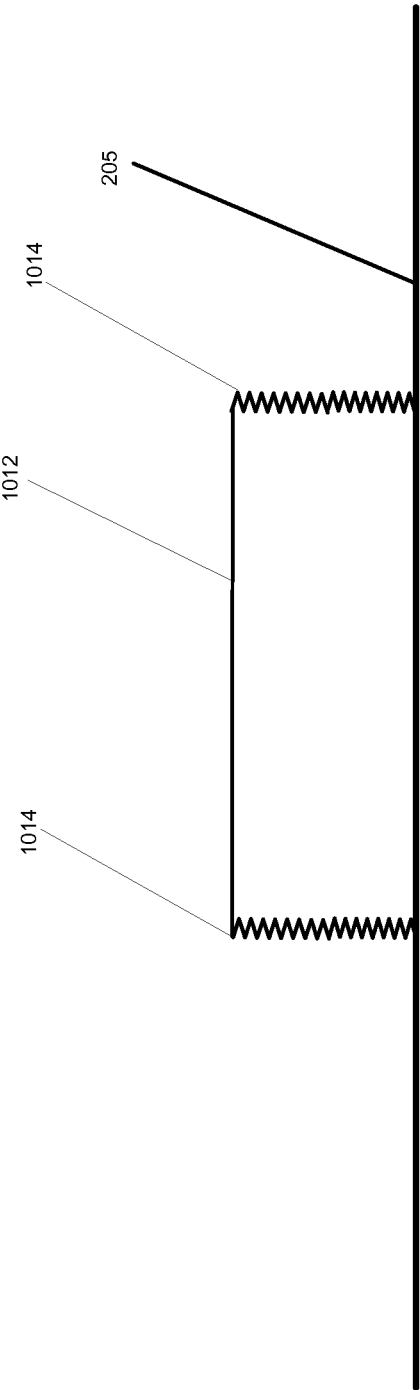


Fig. 10a

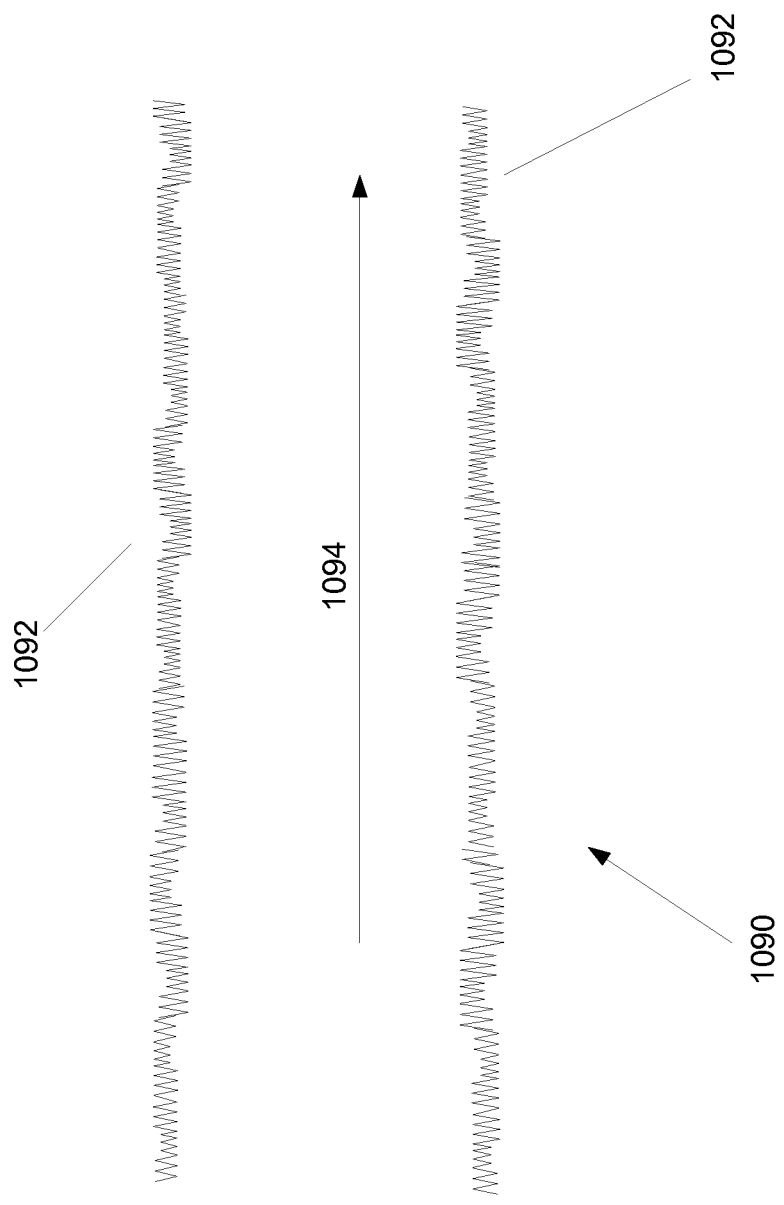


Fig. 10b

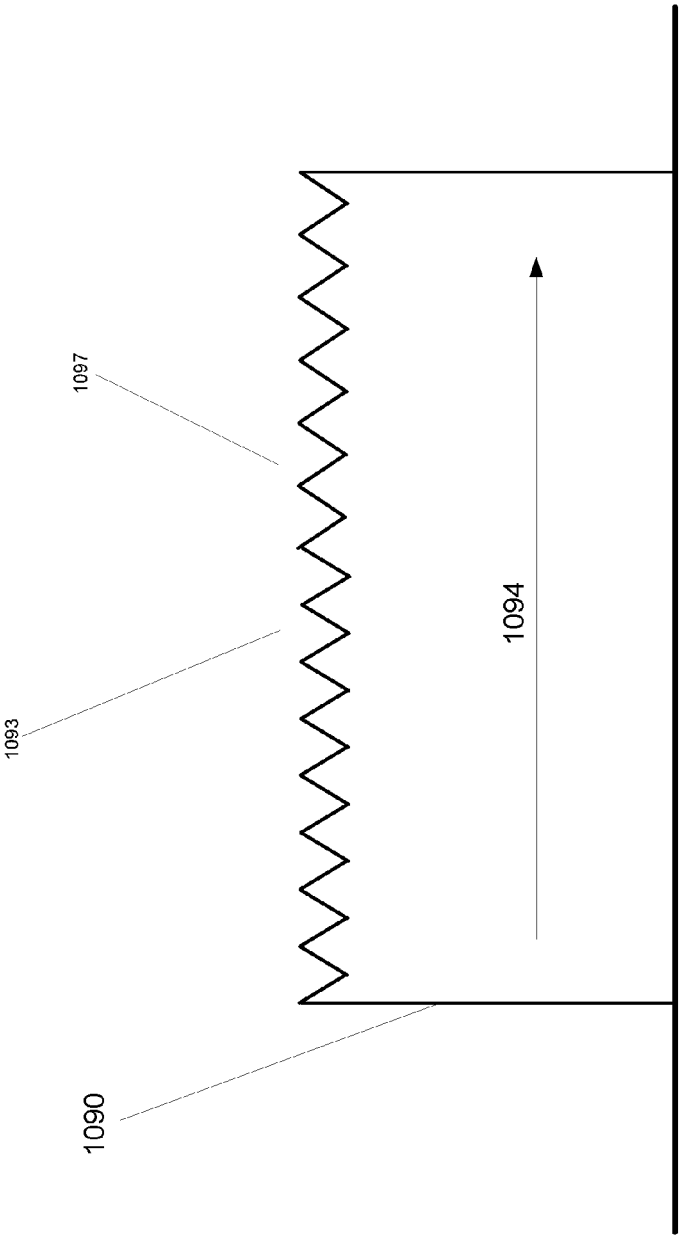


Fig. 10c

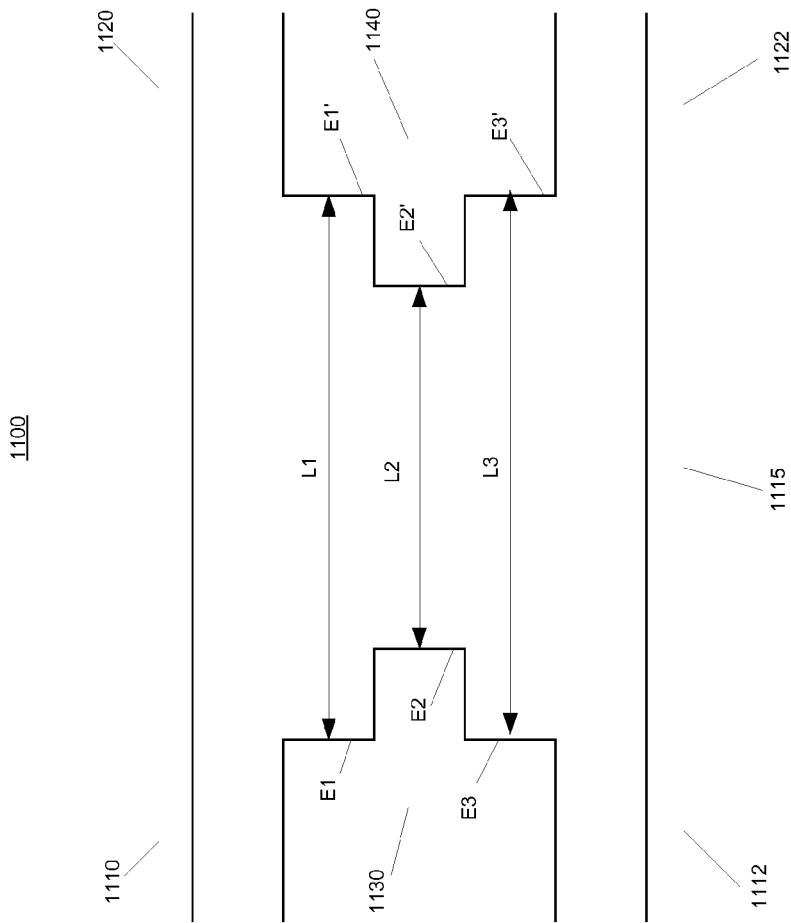


Fig. 11

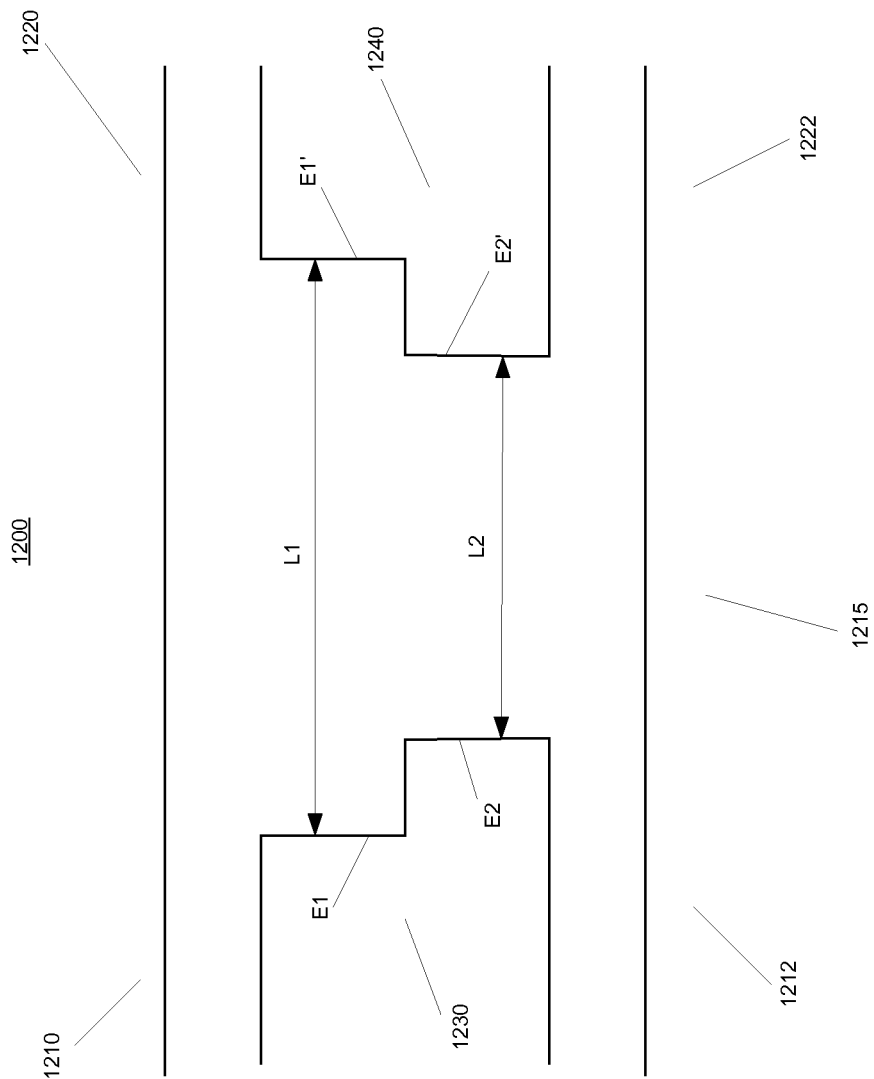


Fig. 12

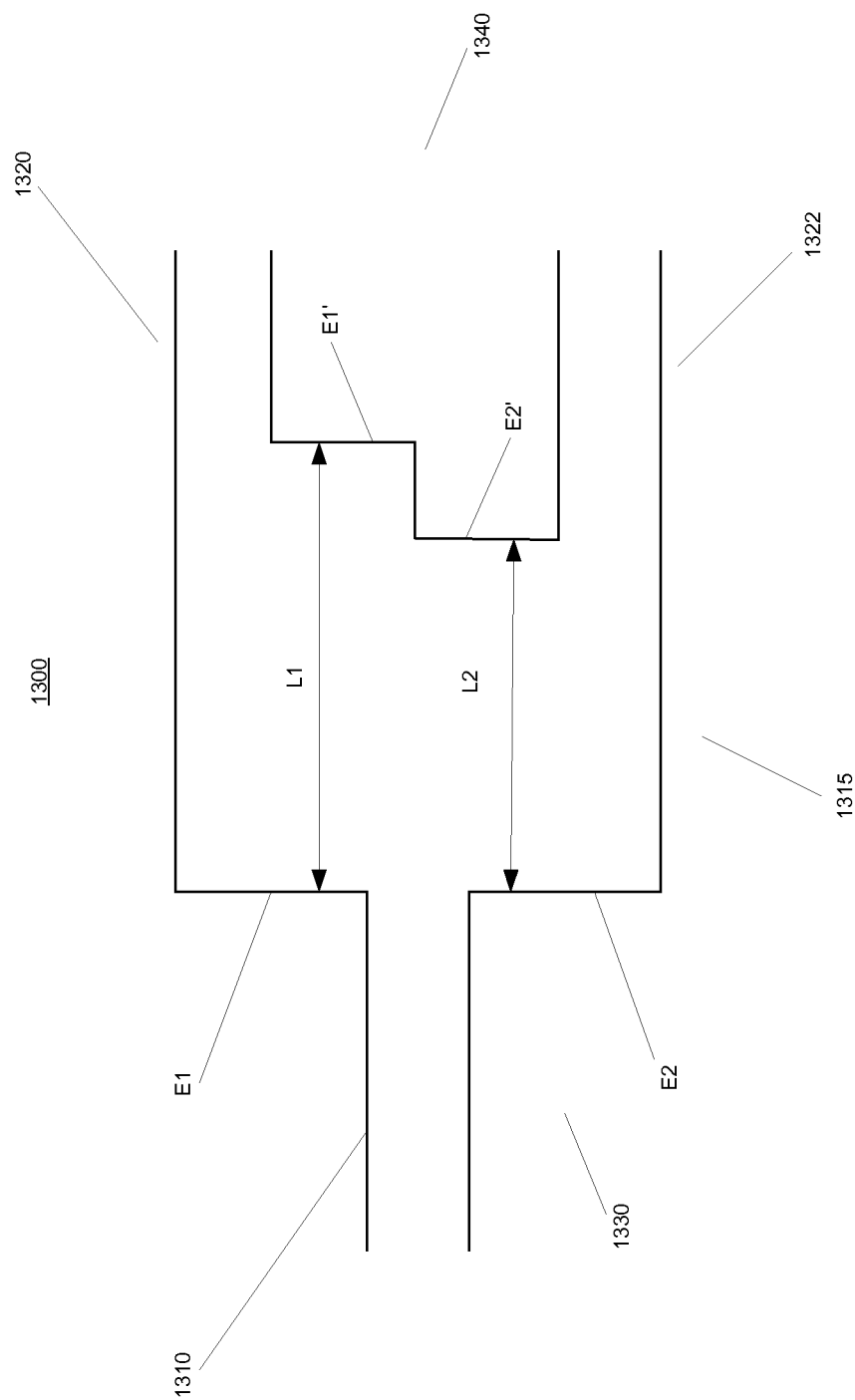


Fig. 13

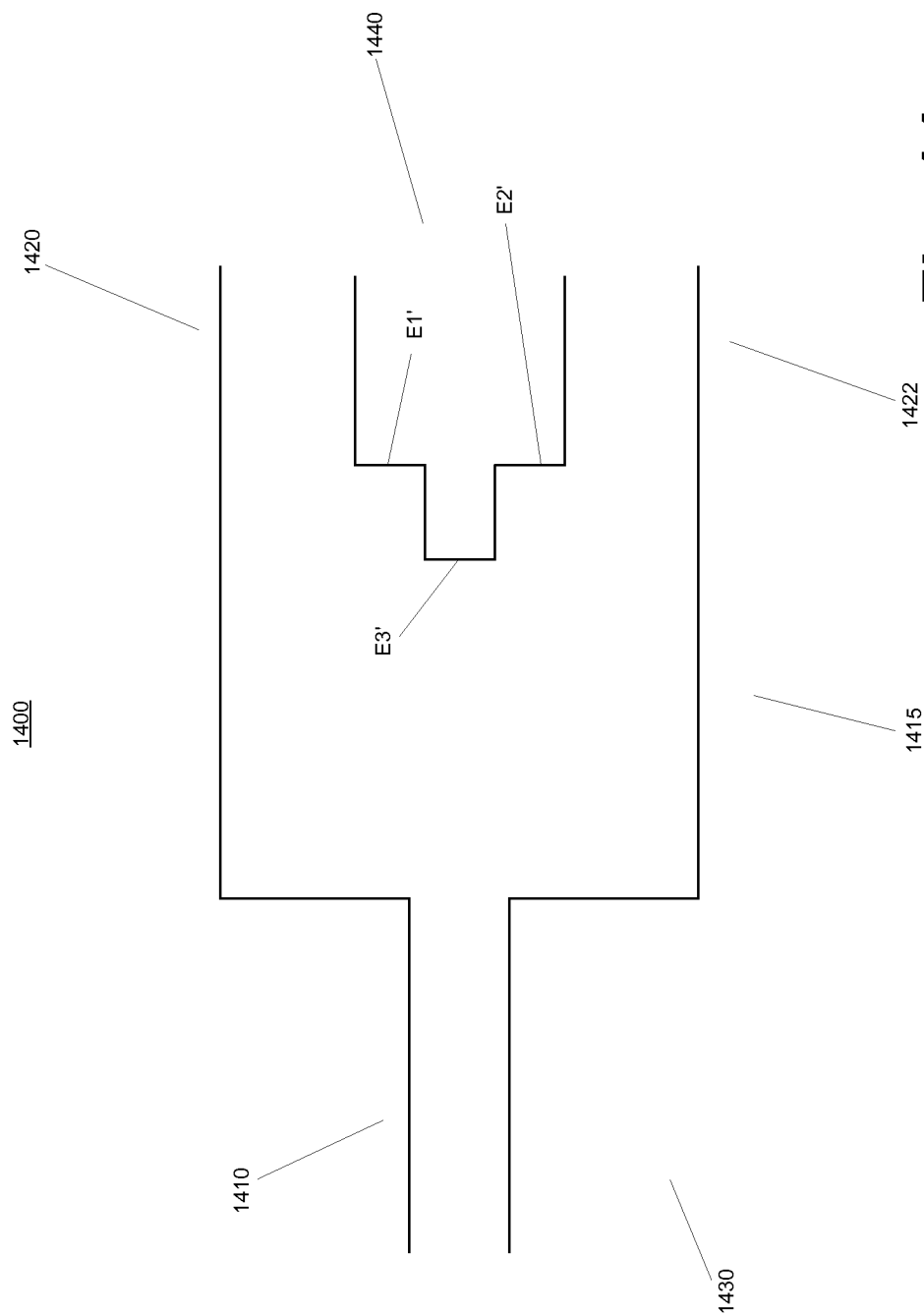


Fig. 14

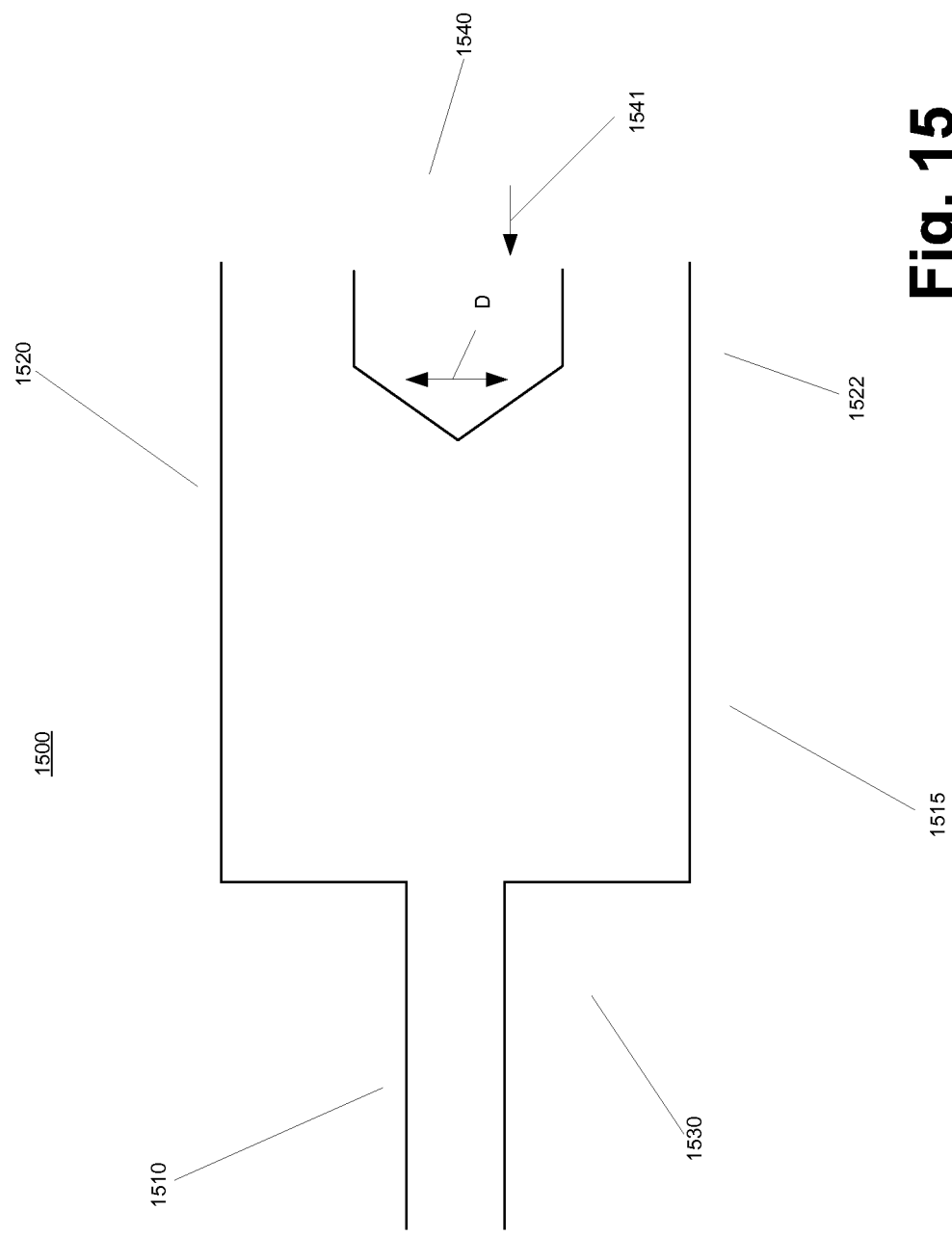


Fig. 15

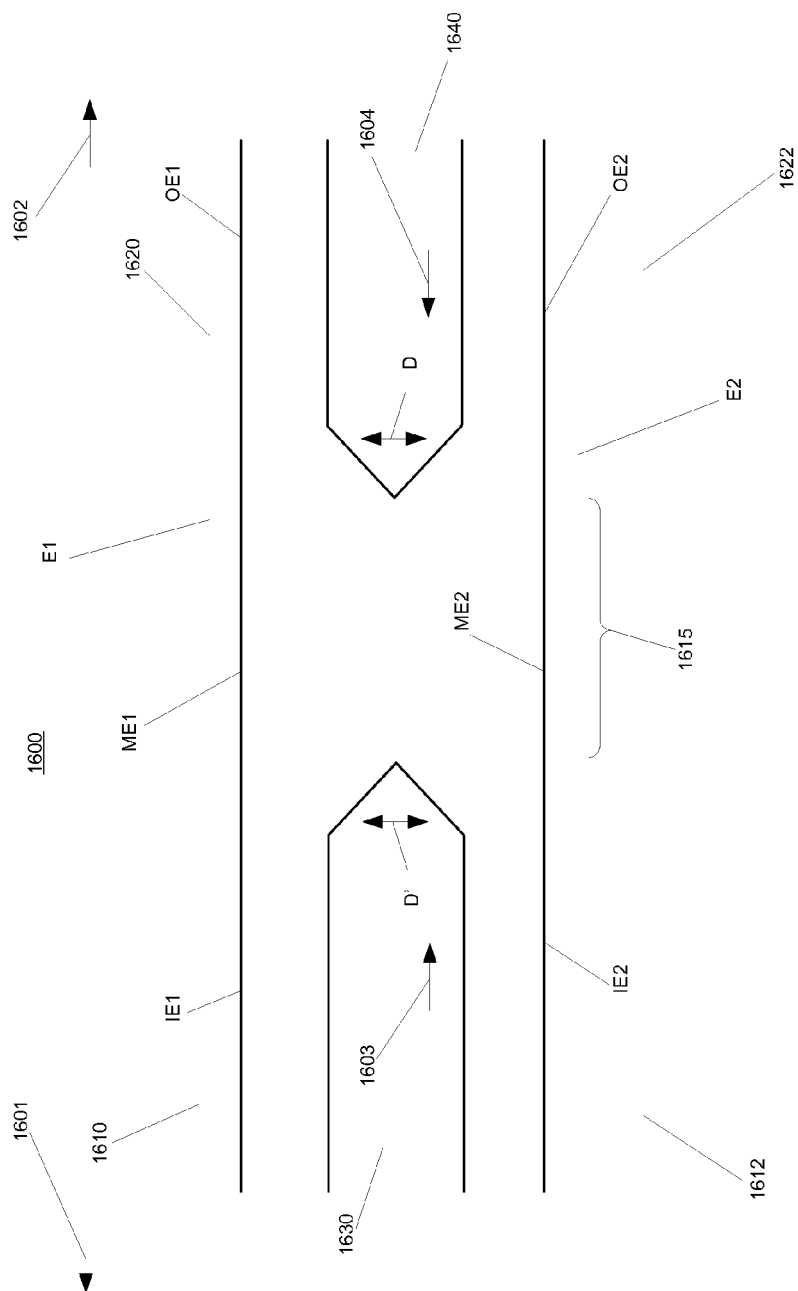


Fig. 16

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LIGHT ABSORPTION AND SCATTERING DEVICES IN A PHOTONIC INTEGRATED CIRCUIT THAT MINIMIZE OPTICAL FEEDBACK AND NOISE

BACKGROUND

Wavelength division multiplexed (WDM) optical communication systems are known in which multiple optical transmitters supply each of a corresponding one of a plurality of modulated optical signals. The optical signals may be combined by an optical combiner or multiplexer in a transmit node and supplied to an end of an optical communication path. The combined optical signals may then propagate along the optical communication path to a receive node, where the optical signals are demultiplexed and each is supplied to a corresponding optical receiver.

Each optical transmitter may include a laser that outputs light having a particular wavelength and a modulator that modulates the light in accordance with a data stream to provide a respective one of the modulated optical signals. Other optical components may also be provided. Typically, optical fibers or other waveguides are provided to direct light from one component to the next, e.g., from the laser to the modulator, and from the modulator to the combiner. An interface may exist between an end face of the fiber and part of the component that receives the light. Light may scatter at such interfaces, and such scattered light may be fed back to the laser and interfere with the operation of the laser. Alternatively, the scattered light may interfere with optical signals propagating in the waveguides. Often the waveguides are tilted or angled in such a way as to reduce such scattering back into the source waveguides and the lasers whereby the waveguide may “dodge” the scattered light.

In another example, the optical combiners or couplers may include a portion through which unwanted portions of the combined optical signals may escape. Such light may also constitute undesired feedback to the lasers as well as interfere with optical signals propagating in the waveguides. Accordingly, additional waveguides may be provided at such “dump ports” to direct the undesired light away from waveguides carrying optical signals and the lasers.

Conventional WDM optical communication systems often include discrete components, such that, for example, the lasers, modulators, and other components are housed separately from one another or provided on separate substrates. Other WDM optical communication systems, however, include photonic integrated circuits (PICs) in which these components may be integrated on a common substrate. As the density and size of PICs increases, the conventional approaches to reducing scattered light may be impractical due to the layout or configuration of various components on the PIC.

Accordingly, there is a need for devices that can be readily integrated on a PIC and reduce unwanted light.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate one or more implementations described herein and, together with the description, explain these implementations. In the drawings:

FIG. 1 illustrates a block diagram of an optical communication system consistent with the present disclosure;

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FIG. 2a illustrates a block diagram of an example of an optical transmitter block consistent with a further aspect of the present disclosure;

FIG. 2b illustrates an example biased element consistent with a further aspect of the present disclosure;

FIG. 3 illustrates an arrayed waveguide grating (AWG) consistent with an additional aspect of the present disclosure;

FIG. 4 is an enlarged view of a portion of the AWG shown in FIG. 3;

FIGS. 5-7a, and FIG. 7b are diagrams of example absorptive structures; and

FIGS. 8-10c are diagrams of example scattering structures.

FIGS. 11-15 illustrate examples of multi-mode interference (MMI) structures consistent with further aspects of the present disclosure; and

FIG. 16 shows an example of a low reflection 2x2 MMI coupler.

DETAILED DESCRIPTION

The following detailed description refers to the accompanying drawings. The same reference numbers in different drawings may identify the same or similar elements.

Various devices are proposed to minimize optical feedback to the laser or optical noise in the signals supplied from the output waveguides of the PIC. For example, devices may be provided to capture and absorb unintentionally scattered light that escapes from a waveguide or is present in the substrate. In another example, structures may be provided to disperse or scatter light output from a dump port of a coupler. As used herein, a “dump port” is a waveguide that supplies guided optical light that is not intended as an optical or electrical output.

The devices may include semiconductor layers that constitute other components on the PIC and thus may be easily manufactured and readily integrated on the PIC. These devices may include a waveguide core that captures unguided light, and a layer, such as a metal, that absorbs the captured light. In one example, a spiral waveguide is provided, as a scattering structure, and in another example, a multi-mode interference (MMI) device is provided that has a tapered structure. Alternatively, combinations of these devices may be provided at various locations on the same PIC.

In one implementation, the absorbing and/or scattering devices can be placed in locations along a path or adjacent to a path between where the unwanted light originated and where the unwanted light can interfere with an optical signal (from wanted light) being received by the receiver. For example, the absorbing and/or scattering devices can be placed near the optical sources, near waveguides, and/or near the multiplexers or receivers.

Additionally, the absorbing and/or scattering devices can be located at locations where scattering may be expected to occur, such as at places of device discontinuity, bends in a waveguide, and/or locations where light is intentionally scattered. For example, the absorbing and/or scattering devices can be placed near devices in the PICs, at bends in the waveguides, and/or at guided terminal ports (e.g., input ports, output ports or dump ports) or terminal ends of waveguides. Further, structures consistent with the present disclosure may be provided at transitions between different wave-guiding structures (e.g., transitions between epitaxial layers, such as a butt joint, and transitions between deep and shallow-etched waveguide).

In one or more implementations, absorbing devices can include band gap absorption devices, metallic absorption devices, and/or absorptive guidance devices, and scattering

devices can include optical devices that scatter light using geometric structures. By absorbing unintentionally scattered light and scattering light from a coupler dump port, for example, optical feedback to the laser is minimized which would otherwise cause broadening of the laser line-width. In addition, phase, amplitude, and spectral noise in the optical signals output from the PIC is reduced. Scattering and capturing/absorbing devices, as disclosed herein are passive, and do not require application an electrical bias, such as a current or voltage bias, as in the case of known active absorption techniques. Accordingly, the devices disclosed herein do not consume power and dissipate minimal power through passive absorption, which may include grounding various diode structures discussed below. As a result, scattering and light capturing/absorbing structures consistent with the present disclosure do not appreciably heat the PIC, as opposed to active absorption devices. Reverse-biasing the diodes disclosed herein can improve absorption efficiency, but with increased power consumption. Such reverse biasing, however, is unnecessary.

Further, the structures disclosed herein may include the same epitaxial layers as other devices in a PIC. In addition, there is no need to rout the undesired light off the substrate or PIC. More compact PIC layouts can minimize power consumption.

An exemplary system which may include absorbing and/or scattering devices will next be described below with reference to FIGS. 1-3. Detailed descriptions of examples of the absorbing and/or scattering devices follow the system description.

FIG. 1 illustrates an optical link or optical communication system **100** consistent with an aspect of the present disclosure. Optical communication system **100** include a transmit node **11**, which may have a plurality of photonic integrated circuits (TxPIC-1 to TxPIC-n, collectively to herein as a TxPICs). Each TxPIC may further include a plurality of transmitter blocks (Tx Block) **12-1** to **12-n** provided. Each of transmitter blocks **12-1** to **12-n** receives a corresponding drive signals associated information streams Data-1 to Data-n supplied to node **11**. In response to such drive signals, each of transmitter blocks **12-1** to **12-n** may output a group of optical signals or channels to a combiner or multiplexer **13-1**. Each optical signal carries an information stream or data corresponding to each of data streams Data-1 to Data-n. Multiplexer **13-1**, which may include one or more optical filters, for example, combines each of group of optical signals into a wavelength division multiplexed (WDM) that is output to an additional multiplexer **13-2**, that combines the optical signal outputs from each TxPIC onto optical communication path **14**. Optical communication path **14** may include one or more segments of optical fiber and optical amplifiers, for example, to optically amplify or boost the power of the transmitted optical signals.

As further shown in FIG. 1, a receive node **18** may also be provided that includes an optical decombining or demultiplexer **15-1**, which may include one or more optical filters or deinterleavers. For example, optical demultiplexer **15-1** may supply each group of received optical signals to a corresponding one of receiver photonic integrated circuit (RxPIC-1 to RxPIC-n, collectively or individually referred to herein as RxPICs) **22-1** to **22-n**. Each RxPIC has a demultiplexer **15-2**, which supplies each optical signal within each group to a corresponding one of receiver blocks **22-1** to **22-n**. Each receiver block, in turn generates corresponding electrical signals, which are then processed by various circuitry (not shown in FIG. 1) to output copies of data streams Data-1 to Data-n from receive node **18**. It is understood that each of the

remaining TxPICs in node and each of the RxPICs in node **18** may operate in a manner similar to that discussed above to supply data carrying along optical communication path **14**.

One of transmitter blocks **12-1** is shown in greater detail in FIG. 2. It is understood that remaining transmitter circuitry or blocks **12-2** to **12-n** have the same or similar structure as transmitter block **12-1**. Transmitter block **12-1** may include a substrate **20** and a laser **20-1** that may be provided on the substrate. Alternatively, laser **20-1** may be provided as a discrete device spaced from substrate **20**. Laser **20-1** may be operated in a continuous wave (CW) mode to continuously output light to a modulator, such as a Mach-Zehnder modulator **21**. Modulator **21** may include a first coupler, such as a multi-mode interference (MMI) coupler **21-1**, and a second coupler **21-6**, such as MMI coupler **21-6**, as well as first and second waveguides or arms **21-2** and **21-3** extending therebetween. A known phase shifter (e.g., 90 degrees) **21-7** may also be provided to shift the phase of light propagating in arm **21-3**. Drive signals may be applied to electrodes **21-4** and **21-5** to vary a bias applied to arms **21-2** and **21-3**, respectively, in accordance with data carried by each drive signal. In response to such varying bias, the refractive index of each arm changes, such that the phase of light propagating in each arm also changes. As a result, when light from each arm **21-2** and **21-3** is combined in coupler **21-6**, the phase and/or amplitude of light output from port **21-9** of coupler **21-6** is varied in accordance with the data associated with the drive signals supplied to electrodes **21-4** and **21-5**.

It is noted that a so-called “nested Mach-Zehnder” modulator may also be provided instead of the modulator configuration shown in FIG. 2. In the “nested configuration” the light output from laser **20-1** may be split into first and second portions, which are supplied to first and second Mach-Zehnder modulators, respectively. These modulators, in turn, may phase and/or amplitude modulate the light supplied thereto, and the outputs of the modulators may then be combined. Optical signals output from “nested” modulators may carry data at twice the rate as modulators having the structure shown in FIG. 2. In addition, two such nested modulators can be provided in a polarization multiplexed configuration. An example of such a configuration is described, for example, in U.S. patent application Ser. No. 12/981,835 filed Dec. 30, 2010, the entire contents of which are incorporated herein by reference.

As further shown in FIG. 2, coupler **21-6** has a so-called “dump port”, which, as noted above, outputs unwanted light resulting from optical interactions within coupler **21-6**. Consistent with the present disclosure, however, an integrated absorbing or scattering structure **25**, for example, may be provided at dump port **21-8** to absorb such unwanted light. Various exemplary structures suitable for absorbing and/or scattering unwanted light are discussed in greater detail below with reference with FIGS. 5-7a, 7b, 8-10a, and 10b.

Typically, structure **25** is not biased with a voltage. However, a biased element **25-b** may optionally be provided in addition to structure **25** to absorb any light that is not absorbed or scattered by structure **25**. Element **25-b** will next be described in greater detail below with reference to FIG. 2b.

As shown in FIG. 2b, element **25-b** may have a diode structure including a p-type semiconductor region **25-p** and an n-type region **25-n** provided on substrate **20**. A power supply **27** may also be provided to reverse bias element **25-b**. As a result, residual light output from structure **25** may be absorbed by a depletion region (not shown) formed at a junction between regions **25-p** and **25-n**.

As noted above, optical signals output from node **11** and multiplexer **13-2** propagate along optical communication

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path 14 to receive node 18, where the optical signals are separated into groups by demultiplexer 15-1, and each optical signal group is provided to a respective one of RxPIC-1 to RxPIC-n. In RxPIC-1, one of the optical signal groups is demultiplexed by demultiplexer 15-2 and each optical signal in that group is supplied to corresponding one of receivers (Rx) 17-1 to 17-n.

In one example, demultiplexer 15-2 may include an arrayed waveguide grating (AWG), such as AWG 32 shown in FIG. 3. AWG 32 may include an input waveguide 31 which supplies the optical signal group to a free space region or first dielectric slab 33. AWG 32 also includes waveguides, also referred to as grating waveguides 35, and a second dielectric slab 37. As generally understood, the lengths, widths, and other dimensions/properties of slabs 33 and 37, as well as waveguides 35, may be selected so that AWG 32 may be configured as an optical demultiplexer to supply each optical signal to a respective one of output waveguides 26. Each of output waveguides 26, in turn, provides a respective optical signal to a corresponding one of receivers 17-1 to 17-n. As generally understood, in the demultiplexer configuration, each optical signal is directed to or focused on to an edge of slab 37 adjacent a corresponding one of waveguides 26.

FIG. 4 shows a portion of AWG 32 including second slab 37 in greater detail. In this example, reflection suppression structures in the form of waveguide structures 50, 52 and 54 adjacent a substantial number of focal points 40' are provided, such that relatively little light remains to reflect off the output interface 18B of slab 37. Since there are losses associated with the reflected light, waveguides 50, 52 do not need to be placed adjacent each and every focal point as the reflected light from some focal points will lack sufficient energy to pass back through AWG 37. Moreover, some of these focal points 40 may be within a higher order Brillouin zone, and therefore be of lower power. Waveguides 50 are fabricated such that a first end portion of the waveguide 50 is coupled to the output interface 18B at a point adjacent to a focal point 40, guiding the light energy from second slab 37 to the respective waveguide 50. As depicted, a second end portion or distal end of each waveguide 50 includes a tapered portion 50' which dissipates the optical energy within the surrounding substrate. More specifically, as the light enters the tapered portion 50' of the distal end of waveguide 50 the mode of such light expands, and the light is absorbed in the surrounding substrate.

Alternatively, waveguides can be constructed to couple the light energy associated with any one focal point on an edge of slab 37 to a light absorbing material. For example, as further shown in FIG. 4, a waveguide 52 can couple the light energy of the associated focal point 40 to a light capturing or absorbing/capturing structure AB, examples of which are discussed below. Waveguide 52 can be curved away from the main signal channel grouping, as shown, to further move the light energy away from the signal channel waveguides 26 to minimize contamination of the signal channels. Additionally, multiple waveguides may be directed to a well of light absorption material. For example, as depicted, waveguides 54 may each couple the light energy of an associated focal point 40 to the light absorbing material AB. Absorbing material AB may be any suitable material which will absorb light energy to reduce, or otherwise suppress, reflection of the associated light. Such optical energy absorbing materials include any semiconductor material, or other material, with a band gap smaller than the propagating light, such as InGaAs or InGaAsP. While it is preferably to couple the light absorbing material AB to slab 37 through the use of one or more waveguides 26' due to space constraints, light absorbing

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material AB can be positioned adjacent to the output interface 18B without the need for waveguides 26'. While not necessary, the waveguides 26' may include curved portions to move the light energy away from the waveguide 26 and the signal channels traveling along the waveguides 26, isolating the light energy from the signals channels and minimizing any optical interference with the light energy of waveguides 26. Additionally, the curved waveguide portions depicted herein for illustrative purposes and are not drawn to scale. As one of ordinary skill would appreciate, such curved waveguide portions can impact the light energy due to their corresponding radius of curvature, therefore waveguides 26' preferably include curved portions to provide better optical isolation while maintaining the integrity of the optical output signal channels transmitted by waveguides 26. Examples of AWG configurations are also described in U.S. Pat. No. 7,974,504, the entire contents of which are incorporated herein by reference. Similarly, as depicted, a waveguide 26' may be coupled to the output free space region 18 of AWG 14 at the location of one of the focal points 40, coupling the corresponding signal channel to an active device, such as photodetector 28', similar to photodetector 28 for example. In this case, no reflected optical energy from the photodiode 28' or waveguide 26' back toward the output free space region 18 is perceived, the light energy optically transmitted from the output free space region 18 through the waveguide 16' and to the photodetector 28' where the light energy is absorbed. It should be noted that a photodetector, such as photodetector 28', can be positioned on the input interface 16A of input free space region 16 to measure optical energy which is representative of the amount of light which is reflected off the various interfaces 16B, 18A, and 18B, back into AWG 14.

Thus light absorbing/scattering structures may be provided in both the TxPICs and RxPICs. Examples of such structures will next be described with reference to FIGS. 5-10b. Namely, FIGS. 5-10b illustrate example implementations of light capturing/absorptive structures AB shown in FIG. 4. Light capturing/absorptive structures AB can be made of a variety of materials and can be made in a variety of configurations.

FIG. 5 is a diagram of an example implementation of a guided absorptive/scattering AB with absorptive core structure 500 that includes an absorptive core, which can absorb unwanted guided light. In one implementation, absorptive core structure 500, a cross-section of which is shown in FIG. 5, can include p-contact 510, first p-type layer 520, second p-type layer 530, n-type layer 550, and n-contacts 560, along with light absorptive core 540, which may include intentionally undoped or intrinsic semiconductor material. In one implementation, first p-type layer 520 can include AlGaInAs, GaInAsP or GaInAs, second p-type layer 530 can include InP or AlInAs, n-type layer 550 can include InP or AlInAs, and light absorptive core 540 can include a semiconductor material, such as GaInAs, GaInAsP or AlGaInAs, and can include a bulk layer, quantum wells and barriers, quantum dots or the like. In another implementation, first p-type layer 520 can include other p-type semiconductor materials, such as GaAs, AlGaAs or GaN, second p-type layer 530 can include other p-type semiconductor materials, such as GaAs, AlGaAs, AlGaIn or GaN, n-type layer 550 can include other n-type materials, such as GaAs, AlGaAs, AlGaIn or GaN, and light absorbent core 540 can include a semiconductor, such as GaAs, AlGaAs, InGaAs, GaN or InGaIn. In another implementation, absorptive core structure 500 can include additional layers, different layers, or fewer layers.

Light absorptive core 540 can be made of any light-absorptive material that can provide band gap absorption of the stray

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light, such as a semiconductor or semiconductor compound or another band gap absorptive material with an appropriate band gap (e.g., C-band (1530-1560 nm), S-band (1460-1530 nm)). In one implementation, the material for light-absorptive core **540** can be chosen for absorbing light (e.g., unwanted light) based upon the frequency of the light produced by a nearby light source. For example, if an optical source, such as a laser in transmitter block **12-1**, is creating light at a particular frequency, then the stray light would be at the same particular frequency, and the absorptive core material can be chosen to absorb light at the particular frequency (or at other frequencies of adjacent optical sources including or excluding the particular frequency).

As illustrated in FIG. 5, absorptive core structure **500** can include a resistor or diode geometry with light absorptive core **540** located within the geometry. In a diode geometry, structure **500** includes contact **510** and contacts **560**. In one example, contacts **510** and **560** may include a metal or other suitable conductor. In addition, p-type layers **520** and **530** are provided, and an n-type layer **550** is provided between the contacts **510** and **560**. Typically, when structure **500** has a diode geometry, a reverse bias (e.g., connecting p-type contact **510** with a negative terminal and connecting n-contacts **560** with a positive terminal) may be applied which to increase the amount of light that can be absorbed by light absorptive core **540**.

In addition, to the diode geometry described above, structure **500** may constitute a resistor. In that case, each of layers **520**, **530**, **540**, and **550** may have the same conductivity type. FIG. 6 is a diagram of an example implementation of light capturing/absorptive structure **600**. Here, structure **600** includes an optional cladding layer **640** and a core layer **630**, which are configured to capture unguided or scattered light in substrate **205**. Metal layer **610**, which may include a refractory metal, has an appropriate thickness to absorb light that is captured in core **630**. In one implementation, an additional cladding layer **620** is provided between metal layer **610** and core layer **630**. Cladding layer **620**, however, is unnecessary if core layer **630** has sufficient optical thickness. In addition, core layer **630** may be absorptive, and cladding layers **620** and **640** may include InP. Preferably, the refractive index of cladding layers **620** and **640** is less than core layer **630**. In another implementation, metal containing absorptive structure **600** can include additional layers, different layers, or fewer layers than that shown in FIG. 6.

As noted above, absorptive metal layer **610** may be provided to absorb light captured by core layer **630** that was unguided in PIC **206**. For example, absorptive metal layer **610** can be used to absorb light that was unintentionally scattered due to light escaping from a waveguide or any guided component of PIC **206**.

Absorptive metal layer **610** may be a light absorbing layer including any metal, such as Ti, W, Al, Au, or combinations thereof, e.g., alloys or multiple metal layers. The amount of light absorbed can depend on material properties, such as composition, temperature, surface roughness, oxide layers and contamination, and also the device geometry that can enhance overlap of guided light to the absorptive metal. In addition, core layer **630** may capture scattered light from underlying layers or the substrate into a guided mode having significant overlap with the absorptive metal **610**, thereby enhancing overall efficiency of the absorptive structure.

FIG. 7a is a diagram of an example implementation of a guided absorptive/scattering structure AB, with Light Absorbing Metal (LAM) structure **700-a** that includes a LAM, which can absorb unwanted guided light. In one implementation, LAM structure **700-a**, a cross-section of which is

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shown in FIG. 7, can include LAM layer **710**, p-type material layer **720**, guiding core layer **730**, and n-type material layer **740**. In another implementation, LAM structure **700-a** can include additional layers, different layers, or fewer layers.

In one exemplary implementation, undoped or p-type material layer **720** can include InP, and undoped or n-type material layer **740** can include InP. Additionally, or alternatively, LAM structure **700-a** may be passive and can be provided with LAM layer **710** on three sides of optical core layer **730** provided that LAM layer **710** is sufficiently close to optical core **730** to absorb light, but not so close as to prevent light from being guided. LAM layer **710** may assist in absorption of unwanted light in PIC **206** by absorbing guided light, such as light from a dump port. LAM layer **710** may be a light absorbing layer including any metal, such as Ti, W, Al, Au, or combinations thereof, e.g., alloys or multiple metal layers. FIG. 7b shows an alternative LAM structure **700-b**, which is similar to LAM structure **700-a**, but includes a relatively thin dielectric layer **715** beneath LAM layer **710**. Preferably, dielectric layer **715** is sufficiently thin so that it can be penetrated by the guided light and absorbed by LAM layer **710**. The thickness and refractive index of layer **715** can also be chosen to maximize light absorption in the guided structure **700-b**, for example, to minimize coupling loss from a waveguide to the absorptive structure. The thickness of refractive index layer **715** may also minimize the input and absorbing section.

FIG. 8 is a diagram of an example implementation of a guided absorptive/scattering structure AB including spiral waveguide structure **800** that can include a spiral configuration at a terminal end of a waveguide to scatter unwanted light guided by the waveguide. Spiral waveguide structure **800** can be used in series with other guided absorptive/scattering structures AB. In one implementation, spiral waveguide structure **800**, a top view of which is shown in FIG. 8, can include a first portion **820** located near a terminal end **810** of waveguide **454**, a second portion **830** that bends upon itself with tight enough radius of curvature to allow light to radiate, and a third portion **840** that terminates to promote scattering more significantly than reflecting. Also note that sections **830** and **840** can have improved performance if the etch depth is reduced by etch loading and/or by mask and etch design. It can also have improved performance if the core is absorptive instead of transparent.

Spiral waveguide structure **800** can be made of the same material as waveguide **454**, and can be shaped to become progressively narrower and spiraled to cause guided light in waveguide **454** to scatter while suppressing back-reflected light.

Additionally, or alternatively, spiral waveguide structure **800** may be fabricated as any sized structure. In one implementation, spiral waveguide structure **800** can be provided if the fabrication process, geometry limitations, or other restraints make absorptive structures (or other scattering structures) impractical or impossible on a TxPIC or RxPIC. For example, a progressively narrowing, spiral waveguide structure **800** can effectively scatter initially guided light with low return loss. As another example, one or more spiral waveguide structures **800** may be fabricated into compact structures that may fit between waveguides or any other components in either the TxPICs or the RxPICs.

FIG. 9 is a plan view of another example of absorptive/scattering structure AB, which includes a "tapered" MMI **900**. MMI **900** may include a single-mode input waveguide **905** that receives undesired or stray light propagating in a direction indicated by arrow **906** from a dump port, for example, or another source. MMI **900** may further include a

multi-mode waveguide section **910**, tapered section **920**, and light output portion **930**. Section **910** may have a constant width $W1$ that extends in a direction transverse to arrow **906**. Section **920**, however, has a tapered width that narrows in the direction of light propagation. Accordingly, as further shown in FIG. 9, section **920** has a width ($W2$) adjacent section **910** that is greater than a width ($W3$) near output portion **930**. Widths $W2$ and $W3$ also extend in a direction transverse to the optical signal propagation direction.

A transition between sections **910** and **920** is abrupt and non-adiabatic. In that case, MMI **900** may be configured so that undesired light is not reflected back to input waveguide **905**. Rather, such undesired light is scattered out the sides of MMI **900** (see arrows **915** and **925**) and/or into the substrate instead.

Tapered MMI device **900** can be made of the same material as waveguide **130**. In another implementation, tapered MMI device **900** can be made of a different material from waveguide **130**, and can include more than one material, including transparent and absorptive materials.

Additionally, or alternatively, tapered MMI device **900** can suppress reflected light from returning to input waveguide **905** by using a combination of tapered MMI device **900** and one or more additional absorptive/scattering structures. In one implementation, tapered MMI device **900** can transmit light away from input waveguide **905**, scatter light **915**, **925**, and direct remaining light to output waveguide **930** that can then be fed into one or more additional absorptive/scattering structures. For example, spiral waveguide structure **800** can be attached to tapered MMI device **900**, such that the input **810** of spiral waveguide structure **800** is attached to output waveguide **930** of tapered MMI device **900**.

FIG. **10a** is a cross-sectional view of another example of a scattering structure including a waveguide **1012** having sidewalls **1014**, which are either chemically or pattern-roughened to provide feature sizes greater than 0.5 microns. Roughened sidewalls **1014** scatter light that may be output from a dump port, such as a dump port of an MMI coupler.

FIG. **10b** is a plan view of a waveguide **1090** having patterned sidewall **1092**. Such patterned sidewalls have feature sizes greater than 0.5 microns and may be configured to scatter light output from a dump port and propagating in waveguide **1090** in a direction indicated by arrow **1094**. Alternatively, the sidewalls may be roughened to have feature sizes less than the wavelength of light propagating in waveguide **1090**. Alternatively, waveguide **1090** may be formed with a periodic pattern or grating to scatter light propagating therein. For example, as shown in FIG. **10c**, a periodic pattern, such as a plurality of grooves constituting a grating **1093**, may be provided, e.g., etched, in surface **1097** of waveguide **1090** to scatter the light.

As discussed herein, guided absorptive/scattering structures **AB** can be specifically selected based on the type of absorbing and/or scattering desired in a particular location and/or for a particular purpose.

Selection of which light capturing/absorptive structures **AB** and can be made based upon several factors, such as space available, aspect ratios, type of unwanted light (guided vs. scattered), or amount of unwanted light. For example, spiral waveguide structures **800** and tapered MMI devices **900** may be fit between waveguides or other components, while other guided absorptive/scattering structures **AB** may not. As another example, metal-absorptive structure **600** can advantageously be selected to be placed after bends in waveguides to absorb unwanted, unguided light that may escape from a first waveguide and potentially interfere with the signal in a second waveguide.

Consistent with a further aspect of the present disclosure, multi-mode interference (MMI) structure may be provided that has reduced reflections. Such structures will next be described with reference to FIGS. **11-15**.

In FIG. **11**, a waveguide **1100** is shown having first (**1110**) and second (**1112**) input portions, which are spaced from one another, at least one of which receives light that propagates in a direction from left to right in the drawing. Waveguide **1100** further includes MMI portion **1115**, as well as first (**1120**) and second output (**1122**) portions, which are spaced from one another. As further shown in FIG. **11**, the first (**1110**) and second (**1112**) input portions extend in a first direction away from first side region **1130** of the MMI portion (**1115**). In addition, the first (**1120**) and second (**1122**) output portions extend away from a second side region (**1140**) of the MMI portion **1115** in a second direction opposite the first direction. Side region **1130** has edges $E1$ to $E3$ between input portions **1110** and **1112**, and side region **1140** has edges $E1'$ to $E3'$ between output portions **1120** and **1122**. $L2$ is typically less than $L1$ and $L3$.

In addition, MMI portion **1115** has a first length $L1$ defined by first edge $E1$ of first side region **1130** and first edge $E1'$ of second side region **1140**. MMI portion **1115** has a second length $L2$ defined by second edge $E2$ of first side region **1130** and edge $E2'$ of second side region **1140**. Further, MMI portion **1115** has third length $L3$ defined by third edge $E3$ of first side region **1130** and third edge $E3'$ of second side region **1140**. Lengths $L1$, $L2$, and $L3$ are in a direction of propagation of light from input portions **1110**, **1112** to output portions **1120**, **1122**. Length $L3$ is typically less than lengths $L1$ and $L2$, which may be equal to one another.

An alternative waveguide **1200** is shown in FIG. **12**. Waveguide **1200** has input portions **1210**, **1212** corresponding to input portions **1110** and **1112**, as well as output portions **1220**, **1222** corresponding to output portions **1120** and **1122** of waveguide **1100** discussed above. In addition, waveguide **1200** MMI portion **1215** and opposing side regions **1230** and **1240**. Side region **1230** has edges $E1$ and $E2$ provided between input portions **1210** and **1212**, and side region **1240** has edges $E1'$ and $E2'$ provided between output portions **1220** and **1222**. In FIG. **12**, first length $L1$ is defined by edges $E1$ and $E1'$, and second length $L2$ is defined by edges $E2$ and $E2'$. Typically, lengths $L1$ and $L2$ are different from one another in this example.

Both waveguides **1100** and **1200** may constitute 2×2 MMI couplers that receive optical signals at the input portions thereof. For example, input portions **1110** and **1112** may receive optical signals having wavelengths λ_1 and λ_2 , respectively. As is generally understood, light input on portion **1100** may be supplied to either one of or both output portions **1120** or **1122** depending on the temperature or geometric parameters, i.e., the dimensions of the MMI region **1115**. Similarly, depending on such parameters, light input on portion **1112** may similarly be supplied to one or both of output portions **1120** to **1122**. Regardless of the desired configuration of MMI regions **1115**, however, in the absence of edges $E1$, $E2$, $E3$ and $E1'$, $E2'$, and $E3'$, light may be reflected in portions of waveguide **1100** between output portions **1220**, **1222** and MMI portion **1215**, i.e., portions where the effective refractive index may change. Such reflections may interfere with the input light causing errors in transmission. Consistent with the present disclosure, however, by providing edges $E1$ - $E3$ and $E1'$ - $E3'$ such reflections are reduced. Edges $E1$, $E2$, $E1'$ and $E2'$ in FIG. **12** also result in reduced reflections. A further exemplary waveguide **1300**, configured as a 1×2 MMI coupler, is shown in FIG. **13**. Waveguide **1300** may include an MMI portion having side regions **1330** and **1340**, with an

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input portion for receiving one or more optical signals extending from side region 1330 in a first direction and output portions 1320 and 1322 extending from side region 1340 in a second direction opposite the first direction. Side region 1330 has edges E1 and E2, with input portion 1310 provided there between, and edges E1' and E2' of side region 1340 are provided between output portion 1320 and output portion 1322.

MMI portion 1315 may have two lengths L1 and L2 in a direction of light propagation from input portion 1310 to one or both of output portions 1320 and 1322. Length L1 is defined by edges E1 and E1' and length L2 is defined by edges E2 and E2'. Lengths L1 and L2 are typically different from one another. Waveguide structure 1300 also has fewer reflections than would otherwise occur in the absence of edges E1, E2, E1' and E2'.

FIG. 14 shows another example of a 1×2 MMI coupler configuration. Here, waveguide 1400 has an input portion 1410, which extends from side region 1430, and output portions 1420 and 1422, which extend from side region 1440. As in waveguide 1300, light propagates in a direction from input portion 1410 to one or both of output portions 1420 and 1422. In the example shown in FIG. 14, side region 1440 has edges E1', E2', and E3', with edge E3' being recessed relative to edges E1' and E2'. MMI region 1415 also has reduced reflections.

In another example shown in FIG. 15, an additional example of a low reflection MMI configuration is shown. Here, the configuration includes a waveguide 1500 that may function as a 1×2 coupler. Waveguide 1500 has an input portion 1510 that receives optical signals and output portions 1520 and 1522, one or both of which may output such optical signals. Waveguide 1500 also has an MMI portion 1515 with side regions 1530 and 1540. Input portion 1510 extends from side region 1530 in a first direction, and output portions 1520 and 1522 extend from side region 1540 in a second direction opposite the first direction. As further shown in FIG. 15, a distance D between output portions 1520 and 1522 narrows in a third direction represented by arrow 1541 toward MMI portion 1515. The direction may be the same or a different direction than the direction in which input portion 1510 extends from side region 1530. MMI portion 1515 also has reduced reflections.

A further example of a low reflection 2×2 MMI coupler will next be described with reference to FIG. 16, which shows waveguide 1600 having first (1610) and second (1612) input portions (for receiving light), an MMI portion 1615, and first (1620) and second (1622) output portions (one or both of which may output light). The first (1610) and second (1612) input portions extend from first side region 1630 of MMI portion 1615 in a first direction (as indicated by arrow 1601) away from first side region 1630 of MMI portion 1615. A distance D' between the first (1610) and second (1612) input portions adjacent MMI portion 1615 narrows in a second direction (as indicated by arrow 1603) toward first side region 1630 of MMI portion 1615.

In addition, the first (1620) and second (1622) output portions extend away from second side region 1640 of MMI portion 1615 in a third direction (as indicated by arrow 1602) away from second side region 1640. Distance D between the first (1620) and second (1622) output portions adjacent MMI portion 1615 narrow in a fourth direction (as indicated by arrow 1604) toward second side region 1640 of MMI portion 1615. That is, both the input and output portions taper toward the MMI portion.

As further shown in FIG. 16, edges IE1, ME1, and OE1, of first input portion 1610, MMI portion 1615, and first output

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portion 1620, respectively, constitute a first uniform or straight edge (E1) of waveguide 1600. In addition, edges IE2, ME2, and OE2, of second input portion 1612, MMI portion 1615, and second output portion 1622, respectively, constitute a second uniform or straight edge (E2) of waveguide 1600.

2×2 MMI couplers having the configuration shown in FIG. 16 have been observed to have a reflectivity of −42 dB, which constitutes reflection suppression of −15 dB relative to a 2×2 MMI coupler without the tapering discussed above.

The foregoing description provides illustration and description, but is not intended to be exhaustive or to limit the embodiments to the precise form disclosed. For example, while the absorptive and scattering structures were described herein as being used in the TxPICs and the RxPICs, the absorptive and/or scattering structures can be used in other optical devices, such as discrete component optical transmitters, receivers, or other optical devices that can have issues with unwanted light. Modifications and variations are possible in light of the above disclosure or may be acquired from practice of the embodiments.

Even though particular combinations of features are recited in the claims and/or disclosed in the specification, these combinations are not intended to limit the disclosure of the possible embodiments. In fact, many of these features may be combined in ways not specifically recited in the claims and/or disclosed in the specification. For example, the absorptive structure may include deep levels, such as degenerately doped semiconductor material, e.g., semiconductor material having an n or p-type impurity concentration of at least $10^{20}/\text{cm}^3$. Alternatively, the absorptive structure may include one or more semi-metals, such as arsenic, carbon, tin, bismuth, mercury telluride or other materials having comparable absorption coefficients.

No element, act, or instruction used in the present application should be construed as critical or essential unless explicitly described as such. Also, as used herein, the article “a” is intended to include one or more items. Where only one item is intended, the term “one” or similar language is used. Further, the phrase “based on” is intended to mean “based, at least in part, on” unless explicitly stated otherwise.

What is claimed is:

1. A photonic integrated circuit comprising:

a substrate;

a coupler provided on the substrate, the coupler having an input port and first and second output ports, the input port receiving an optical signal, the first output port supplying a first portion of the optical signal and the second output port supplying a second portion of the optical signal;

an output waveguide circuit that receives the first portion of the optical signal; and

an integrated structure provided on the substrate at the second output port that scatters part of the second portion of the optical signal without an electrical bias applied to the structure or without routing of the second portion of the optical signal off the substrate.

2. A photonic integrated circuit in accordance with claim 1, wherein the coupler is a multi-mode interference (MMI) coupler and the second output port is a dump port of the MMI coupler.

3. A photonic integrated circuit in accordance with claim 1, wherein the coupler is a first coupler, the photonic integrated circuit further including a Mach-Zehnder interferometer (MZI), the MZI including first and second waveguides extending between the first coupler and second coupler, the second output port being a dump port of the second coupler.

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4. A photonic integrated circuit in accordance with claim 1, wherein the structure includes a spiral-shaped waveguide that receives the second portion of the optical signal.

5. A photonic integrated circuit in accordance with claim 1, further including a waveguide having a width in a first direction that is transverse to a second direction, the optical signal propagating in the waveguide in the second direction, the structure has a first end portion that receives the second portion of the optical signal and a second end portion, the first end portion having a first width and the second end portion having a second width, the first and second widths extending in the first direction, such that a transition from a width of the waveguide to the first width of the first end portion is non-adiabatic and abrupt, and
the second portion of the optical signal propagates in the second direction from the first end portion of the structure to the second end portion of the structure, the first width being greater than the second width.

6. A photonic integrated circuit in accordance with claim 5, wherein the structure is a multi-mode interference coupler.

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7. A photonic integrated circuit in accordance with claim 1, wherein the structure includes a waveguide, the waveguide having a roughened surface with features sizes greater than 0.5 microns.

8. A photonic integrated circuit in accordance with claim 1, the photonic integrated circuit further including a device that absorbs a portion of the scattered light.

9. A photonic integrated circuit in accordance with claim 8, wherein the device includes a cladding layer provided on the substrate, a core layer provided on the cladding layer, and a metal layer provided on the core layer.

10. A photonic integrated circuit in accordance with claim 9, wherein the metal layer include a refractory metal.

11. A photonic integrated circuit in accordance with claim 15 8, wherein the device includes a first cladding layer provided on the substrate, a core layer provided on the first cladding layer, a second cladding layer provided on the core layer, and a metal layer provided on the second cladding layer.

12. A photonic integrated circuit in accordance with claim 20 11, wherein the metal layer include a refractory metal.

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